A. de la Fuente, R. Pérez Leal, A. García Armada (2015). Joint Strategy for LTE Resource Allocation: Multicast Subgrouping & Unicast Transmissions. En *XII Jornadas de Ingeniería Telemática (JITEL 2015). Libro de ponencias. Del 14 al 16 de octubre de 2015. Palma de Mallorca.* pp. 9-15.

Joint Strategy for LTE Resource Allocation: Multicast Subgrouping & Unicast Transmissions

Alejandro de la Fuente, Raquel Perez Leal, Ana Garcia Armada
Department of Signal Theory and Communications
University Carlos III of Madrid
Email: afuente@tsc.uc3m.es, agarcia@tsc.uc3m.es, rpleal@tsc.uc3m.es

***Abstract*—Mobile broadband services are growing rapidly in the last few years due to the deployment of Long Term Evolution (LTE) cellular networks. Among them, multicast services can be provided using Evolved Multimedia Broadcast and Multicast Service (eMBMS), available with 3rd Generation Partnership Project (3GPP) release 9, which can deliver broadcast/multicast content using a single-frequency network mode. This means sending the same multimedia content to a mass audience within a specific area. The utilization of the Conventional Multicast Scheme (CMS) approach for multicast resource allocation presents intrinsic inefficiencies, because of the different channel conditions of the users which demand the service. This paper proposes a Joint Multicast Subgrouping and Unicast Transmissions (JMSUT) strategy for resource allocation, which consists of the use of the multicast and the unicast transmissions, by means of the subframes reserved by the LTE standard for each purpose, to deliver a multicast service. The goal of the JMSUT algorithm is to maximize the service throughput whereas it guarantees the fulfillment of the Quality of Service (QoS) requirements of every user. This paper solves the former maximization problem of the joint resource allocation; on the one hand, splitting the multicast resources into different subgroups that transmit the same content with different Modulation and Coding Scheme (MCS), and on the other hand, the users with worst channel conditions are served by means of the unicast transmissions.**

I. Introduction

Mobile data traffic is growing rapidly in the last few years and this growth is expected to become bigger in the upcoming years, especially in multimedia services. Of course, the growing demand of multimedia services in mobile networks poses new challenges in the way these services can be provided. New techniques must be developed to guarantee the scalability for large amount of users, since in the near future more devices will be connected leading to what is known as "everything connected". In 2020, approximately 25 billion interconnected devices are expected [1].

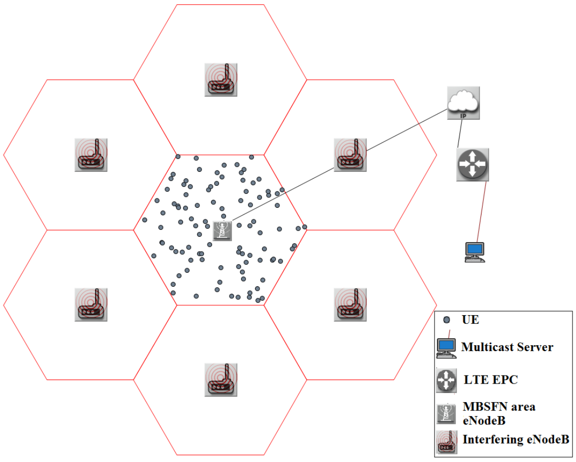
Broadcasting and multicasting are expected to be promising enablers of an easy access to the ubiquitous multimedia experience through mobile terminals [2]. An evolved architecture is required to support Evolved Multimedia Broadcast and Multicast Service (eMBMS) transmission in Long Term Evolution (LTE) network. Such an architecture is detailed in the 3rd Generation Partnership Project (3GPP) specifications [3], there are new logical network entities proposed for eMBMS operation, which enable a point-to-multipoint service that allows data transmissions from a single source to multiple recipients. Consequently, the scalability of broadcast and multicast transmissions in mobile networks is improved. Furthermore, Multicast/Broadcast over Single Frequency Network (MBSFN) has been proposed as an enhancement of eMBMS [3], avoiding the destructive interferences in the areas where the coverage overlaps, and maintaining the performance that would otherwise gradually decrease as User Equipment (UE) moves away from the base station.

While using multicast transmissions improves the efficient utilization of network resources, it requires setting equal transmission parameters to all the users in the MBSFN area. Consequently, in multicast transmissions, the Modulation and Coding Scheme (MCS) is unique and set by upper layers. Therefore, the multicast transmission throughput in the MBSFN area is established by the MCS and the transmission bandwidth [4]. Differently, unicast transmissions can use link adaptation and channel dependent scheduling, based on the Channel Quality Indicator (CQI) the user sends periodically to the Evolved Node B (eNodeB). Therefore, Evolved Universal Terrestrial Radio Access (E-UTRA) can dynamically allocate resources, both the number of Physical Resource Block (PRB) and MCS, to the UEs at each Transmission Time Interval (TTI) [4].

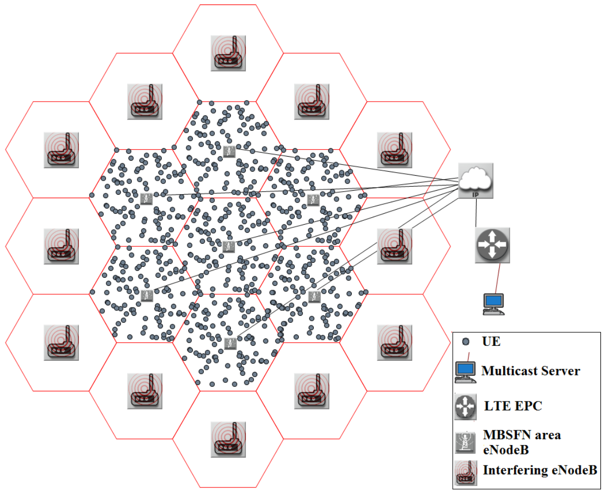
In multicast transmissions, the resource allocation using the Conventional Multicast Scheme (CMS) [5] is based on a conservative approach, where the data rate is restricted by the user that presents worst channel conditions. Of course, this approach maximizes the fairness among multicast users, however the throughput performance in the multicast area is highly inefficient and users with good channel conditions do not achieve as high as possible bit rates.

Recent research, motivated by these issues, studies solutions to improve the multicast service throughput, at the time fairness among users is achieved. In [6], the basic idea of splitting any multicast group into subgroups is utilized and, after that, the strategy applies Adaptive Modulation and Coding (AMC) schemes, which enables a more efficient exploitation of multi-user diversity. This proposal distributes the users into subgroups by solving an optimization problem to improve the service throughput while guaranteeing fairness among multicast members.

In [7], a Joint Multicast/Unicast Scheduling (JMUS) was proposed to maximize the overall throughput in the MBSFN area. The proposed technique combines unicast and multicast transmissions to guarantee a target bit rate for all the users



(a) Single-cell multicast system



(b) Multi-cell multicast system

Fig. 1. System model reference scenario

demanding a multicast service. The optimal MCS used for multicast transmission are obtained each frame. The JMUS with dynamic optimization enhances the Quality of Service (QoS) performance compared to pure unicast, pure multicast, or scheduling techniques without dynamic optimization.

In this paper, we propose a new Joint Multicast Subgrouping and Unicast Transmissions (JMSUT) strategy for resource allocation in an LTE multicast service delivery. This approach combines the unicast transmissions using the LTE subframes reserved for that purpose, and the multicast transmissions using the remaining subframes. The goal of the JMSUT algorithm is to maximize the service throughput whereas it guarantees the fulfillment of the QoS requirements of every user. This paper solves the former maximization problem of the joint resource allocation. On the one hand, the total resources for multicast transmissions are splitted into different subgroups that transmit the same content with different MCS, according to the solution of the joint optimization problem. On the other hand, the users with worst channel conditions are served using a scheduling metric for guaranteed data-rate proposed in [8] to allocate the resources reserved for unicast transmissions. The results presented in this work show that the joint use of multicast subgrouping and unicast transmissions allows important enhancements in the multicast service throughput, at the time the QoS requirements are guaranteed for all the users.

By multicast service we refer to a streaming or downloading service delivered to all the users in the system, while we denote by multicast transmission the utilization of the Physical Multicast Channel (PMCH) by the eNodeB to send the same data to all the users, and by unicast transmission the use of Physical Downlink Shared Channel (PDSCH) by the eNodeB to send the data to each UE [4]. That is, the multicast service can be delivered to a given user by either multicast (shared) or unicast (dedicated) transmission.

The rest of the paper is organized as follows. In Section II, the system model used is described. The proposed JMSUT strategy is detailed in Section III. The results of the performance evaluation are presented in Section IV. Finally, in Section V, the conclusions and future work are explained.

II. System Model

This paper utilizes two reference scenarios deployed to evaluate the resource allocation strategies used to deliver a multicast service in LTE systems.

Fig. 1(a) depicts a single-cell multicast system where an LTE eNodeB provides a multicast service to UEs which are uniformly distributed within the cell. Around this single-cell, a tier of 6 interfering eNodeBs is deployed.

Fig. 1(b) illustrates a multi-cell multicast system, where 7 LTE eNodeBs are coordinated in a single MBSFN. The multicast service is provided in the 7-cell area to UEs which are uniformly distributed within each cell. Around the 7-cell MBSFN area, we consider one tier of 12 eNodeBs operating on the same frequency and transmission power as the 7 eNodeBs in the MBSFN area.

In LTE systems, radio resources are allocated into the time/frequency domain [10]. In the time domain, they are distributed every TTI of 1 ms. Time is organized in frames, each one composed of 10 consecutive TTIs or subframes. In addition, each TTI is made of two time slots with 0.5 ms length. Each time slot corresponds to 7 Orthogonal Frequency Division Multiplexing (OFDM) symbols with normal cyclic prefix (default configuration for unicast transmissions), or 6 OFDM symbols with extended cyclic prefix (recommended for MBSFN configuration for multicast transmissions). In the frequency domain, the total bandwidth is divided in sub-channels of 180 kHz, each one with 12 consecutive 15 kHz

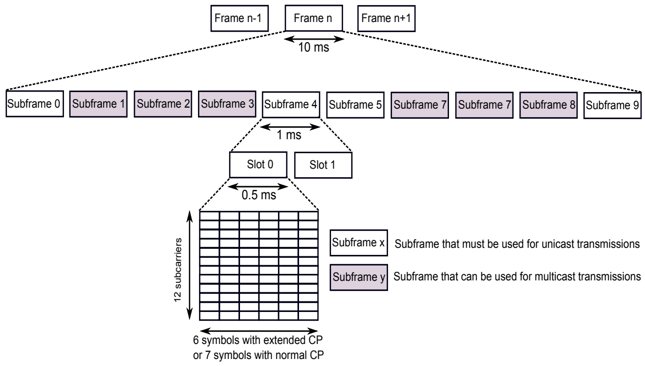


Fig. 2. LTE-FDD frame/subframe structure

OFDM sub-carriers. TheLTE frame/subframe structure for Frequency Division Duplexing (FDD) is illustrated in Fig. 2.

A PRB is the smallest radio resource unit that consists of a 2D radio resource, over two time slots in the time domain, and one sub-channel in the frequency domain. As the sub-channel size is fixed, the number of PRBs varies according to the system bandwidth configuration (e.g. 15 PRBs for system bandwidth of 3 MHz). The PRBs are managed by the packet scheduler in the eNodeB in three phases. Firstly, the information on the schedulable services is collected based on the buffer states. Secondly, in the time domain, the UEs to serve are selected and their QoS constraints are established. Finally, in the frequency domain, the Radio Resource Management (RRM) procedures are executed to meet the QoS constraints.

To implement a channel-aware resource allocation strategy, UEs' CQI are assumed to be known at the eNodeB [5]. CQI is estimated at each UE from the Signal to Interference plus Noise Ratio (SINR) measurement of its radio channel, and sent to the eNodeB using feedback. The eNodeB utilizes this information forwarded by the UEs every CQI Feedback Cycle (CFC) to allocate the resources, determining the MCS used for each unicast transmission.

Furthermore, in multicast mode, the Physical Uplink Control Channel (PUCCH) is used in the uplink to send control messages, e.g. channel state information, from the multicast members to the eNodeB. CQI gives information about the maximum MCS that a UE can decode [4]. LTE systems utilize 15 CQI levels that correspond to the SINR measured by the terminal, and at the same time, these CQIs are related to the maximum MCS supported by the terminal for a correct decoding (refer to Table I). Thus, a UE reporting a determined CQI value can succesfully demodulate only the service delivered with an MCS whose index is equal or lower than the CQI index reported.

eMBMS in LTE systems standardizes the utilization upto 6 subframes of the LTE frame for multicast transmissions using PMCH [3]. The remaining frames (at least 4 subframes) are reserved for unicast transmissions using PDSCH. According to eMBMS standardized service, the resource allocation strategy proposed here searches the solution that allocates jointly, on the one hand, the PRBs in the multicast subframes splitted into different subgroups that deliver the service using different MCS, and on the other hand, the PRBs in the unicast subframes to serve the UEs with worst channel conditions, so that they can fulfill the QoS requirements.

TABLE I
SINR-CQI-MCS MAPPING [9]

SINR (dB)	CQI index	Modulation scheme	Code rate	Spectral Efficiency (bit/s/Hz)
-4.63	1	QPSK	0.076	0.1523
-2.6	2	QPSK	0.120	0.2344
-0.12	3	QPSK	0.190	0.3770
2.26	4	QPSK	0.300	0.6016
4.73	5	QPSK	0.440	0.8770
7.53	6	QPSK	0.590	1.1758
8.67	7	16QAM	0.370	1.4766
11.32	8	16QAM	0.480	1.9141
14.24	9	16QAM	0.600	2.4063
15.21	10	64QAM	0.450	2.7305
18.63	11	64QAM	0.550	3.3223
21.32	12	64QAM	0.650	3.9023
23.47	13	64QAM	0.750	4.5234
28.49	14	64QAM	0.850	5.1152
34.6	15	64QAM	0.930	5.5547

III. RADIO RESOURCE MANAGEMENT STRATEGY USING JMSUT

A multicast service is delivered in an MBSFN area using a dedicated LTE bandwidth. An LTE system can use multicast and unicast transmissions to provide the service to all the users. The proposed RRM strategy uses a JMSUT. On the one hand, the RRM algorithm searches the optimal allocation of the resources in the multicast subframes, splitting them into multicast subgroups that deliver the service using different MCS. On the other hand, the RRM uses the unicast QoS-aware scheduling proposed in [8] to deliver the service using unicast transmissions to the UEs with worst channel conditions. Consequently, the JMSUT aims to maximize the service throughput and, at the same time, guarantees the QoS requirements for all the users demanding the service.

The proposed JMSUT strategy can be splitted into different phases that are described in the following subsections.

A. CQI collection

The first step consists of the collection by the eNodeBs of the CQI feedback from the UEs placed in their MBSFN area which are demanding the multicast service. For each CFC, the eNodeB creates a vector C with all the UEs CQI, such as $C = c_1, c_2, ..., c_n$, where c_i is the CQI reported by user i and n is the number of multicast members served by the eNodeB.

B. Multicast subgroup creation

The proposed JMSUT algorithm splits the multicast member into different multicast subgroups, and the members with worst channel conditions can be attended using unicast transmissions. Each multicast subgroup delivers the service using different MCS in order to serve the users that support the decoding of this scheme with a Block Error Rate (BLER) less than 10% [4].

C. Joint multicast and unicast resource allocation

Radio resources available to deliver the service depend on the bandwidth reserved for that purpose. These PRBs are allocated in multicast subframes (upto 6 subframes of the LTE frame) and unicast subframes.

The resource allocation algorithm proposed works such as whereas a UE reports a CQI that is equal or greater than the lowest multicast subgroup with PRBs allocated, this user will be served by the multicast subgroup closer to the CQI reported and whose MCS can be decoded by the user. On the other hand, only the users which are reporting CQI lower than the lowest multicast subgroup are served using the unicast transmissions reserved in the LTE frame.

Therefore, this algorithm is based on a service throughput maximization problem. This problem presents several constraints, such as the minimum bit rate per user, or the number of PRBs available to deliver the service. The following section describes the Maximum Throughput (MT) algorithm used for this proposal.

D. Maximum Throughput Optimization Problem

The Maximum Throughput (MT) strategy searches to maximize the throughput that can be achieved, enhancing the capacity results obtained using a CMS approach. This strategy is based on a maximization problem of a function cost, that consists of the sum of the data rate of all the members of the multicast service. Furthermore, a minimum bit rate per user has been established to guarantee QoS requirements. Consequently, this maximization problem can be expressed as follows for the reference scenarios:

$$\underset{R}{\text{maximize}} \quad \sum_{i=1}^{n} d_{c_i}^{R} \tag{1}$$

$$\text{subject to} \quad M + U = 10 \tag{1a}$$

$$M \leq 6 \tag{1b}$$

$$d_{c_i}^{R} \geq b_{min} \quad \forall i \tag{1c}$$

$$\sum_{i=1}^{G} r_i = K \tag{1d}$$

$$\sum_{i=1}^{n_u} K_i \leq U \times K \tag{1e}$$

where $R = \{r_1, ..., r_G\}$ is the distribution vector which allocates the PRBs into the different multicast subgroups, $d_{c_i}^{R}$ denotes the bit rate achieved to deliver the service to user i when the distribution vector R is used to allocate the PRBs among the multicast subgroups, and n is the total number of users demanding the multicast service in the MBSFN area. In (1a), M and U denote the number of subframes reserved by the standard for multicast and unicast transmissions in an LTE frame, respectively. In (1b), the maximum number of subframes that can be reserved for multicast transmissions is 6. In (1c), the minimum bit rate that must be guaranteed for all the users is denoted as b_{min}. In (1d), the maximum number of PRBs to allocate is established, so to that end, G denotes the maximum number of multicast subgroups (in LTE there are 15 different CQI sublevels), and K denotes the number of available PRBs per subframe to deliver the service. In (1e), the total cell capacity is ensured not to be surpassed by the unicast transmissions, so n_u denotes the number of users served by unicast transmissions, and K_i is the amount of resources allocated to user i during the LTE frame.

TABLE II
SYSTEM PARAMETERS

Parameter	Value
Multi-cell system size	7 eNodeBs
Interference model	1 tier of eNodeBs
eNodeBs geographical overlay	Hexagonal
Inter site distance	500 m
Transmission power	43 dBm
Antenna gain	11.5
Bandwidth	3 MHz
Number of PRBs	15
Downlink base frequency	2110 MHz
Pathloss model	3GPP Urban Macrocell
Multipath channel model	ITU Pedestrian B
eNodeB transmission antennas	1
UEs per eNodeBs	100
UEs distribution	Uniform distribution
Guaranteed bit rate per user UE	20-200 kbps
Pedestrian user speed	3 Km/h
Vehicular user speed	50 Km/h

IV. Performance Evaluation

The performance evaluation has been carried out using the reference scenarios described in the former section for single-cell and multi-cell multicast system, based on LTE standard. These scenarios use 3 MHz bandwidth, thus 15 PRBs are available to deliver the service. A deployment of 100 users, which are multicast members of the service, has been used with a uniform distribution in each cell. Different combinations of users have been evaluated, using static, pedestrian (mobile users at 3 Km/h) and vehicular (50 Km/h) UEs. The JMSUT algorithm has been used with different QoS constraints, guaranteeing a bit rate between 20 and 200 kbps for all the users. It is worth noting that this performance evaluation has been carried out using a dedicated bandwidth of 3 MHz, therefore higher data rates can be achieved for a multicast service delivered to 100 users reserving more bandwidth for this service. Main simulation parameters are listed in Table II.

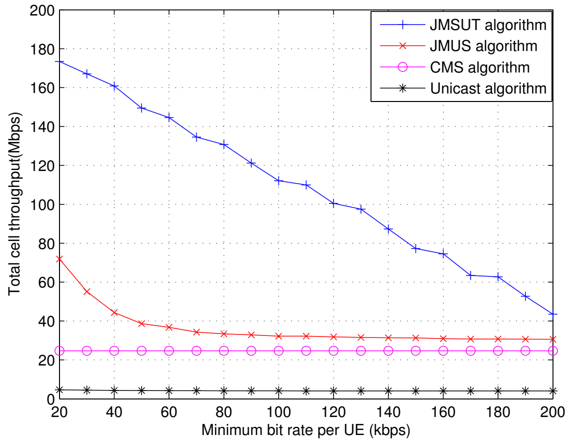


Fig. 3. Performance evaluation using a scenario based on single-cell eMBMS using static and pedestrian users

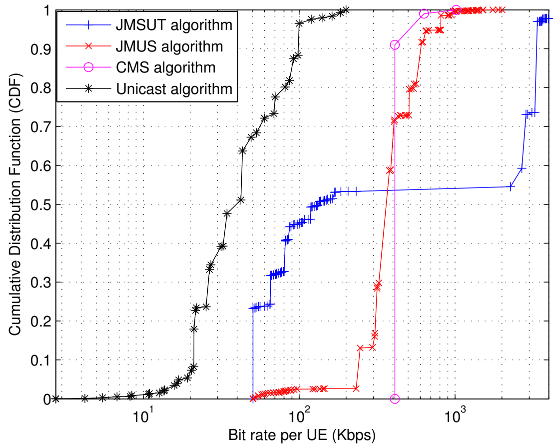


Fig. 4. CDF of users' bit rate in a scenario based on single-cell eMBMS using static and pedestrian users with GBR=50 kbps

This paper shows three different evaluation of the JMSUT strategy use.

The first evaluation consists of a comparison of different resource allocation strategies in a single-cell multicast scenario. The results achieved using the proposed JMSUT strategy are compared with the JMUS proposed in [7], with CMS and with the use of only unicast transmissions.

The second evaluation is based on the multi-cell multicast scenario. A comparison among the results achieved in the central cell and a periferical cell using both JMSUT and JMUS strategies is presented. In addition, these results are compared with the ones achieved in a single-cell multicast deployment.

The third evaluation compares the results obtained with different combinations of users, such as static, pedestrian and vehicular ones.

A. Comparison of different resource allocation strategies in a single-cell multicast scenario

The first evaluation shows the results achieved using different resource allocation strategies in the single-cell multicast scenario with static and pedestrian users.

On the one hand, Fig. 3 illustrates the total service throughput as a function of the minimum bit rate required for every user. It can be noticed that the use of multicast transmissions highly improves the performance of using only unicast transmissions. Nonetheless, the application of joint resource allocation techniques enhances the throughput results with respect of the most conservative multicast scheduling scheme (CMS). Especially with the use of multicast subgrouping, since we can observe how the JMSUT strategy results in important improvements in service throughput over the use of JMUS strategy. However, as the minimum bit rate per user is increased, this gain in total throughput is decreasing. This is because the resource allocation strategy must ensure that users with worst channel conditions reach this minimum bit rate, allocating more resources to the groups that are less efficient in terms of throughput.

On the other hand, Fig. 4 shows the Cumulative Distribution Function (CDF) of the bit rate achieved per UE in this scenario, when the minimum bit rate target is established to 50 kbps. It can be noticed that the minimum bit rate required for all the users cannot be guaranteed using only unicast transmissions. On the opposite side, the utilization of CMS guarantees the maximum fairness among all the users, but at the expense of users with good channel conditions are not having benefit of it, and for that reason the total service throughput is low. On the other side, JMSUT not only allows all the users to achieve the minimum required bit rate, but also users that present good channel conditions can obtain higher bit rates, and consequently the total throughput of the service is greatly increased.

It is worth noting that all the strategies evaluated are using all the resources available in the LTE frame, either using only unicast transmissions or using a combination among multicast and unicast,

B. Comparison of different resource allocation strategies in a multi-cell multicast scenario

The second evaluation illustrates the results obtained using the multi-cell multicast scenario with static and pedestrian users.

In Fig. 5, the service throughput achieved in the central cell and a peripheral one, using both JMSUT and JMUS strategies, are presented. Furthermore, these results are compared with the ones achieved using the single-cell multicast scenario. It can be noticed an important throughput gain obtained in multi-cell scenario, especially in the central cell. The use of coordinated transmissions among 7-cells in an MBSFN area improves the channel conditions of the users in the cell edge, especially in central cell. In addition, this improvement in the channel conditions of the users leads to a higher gain using

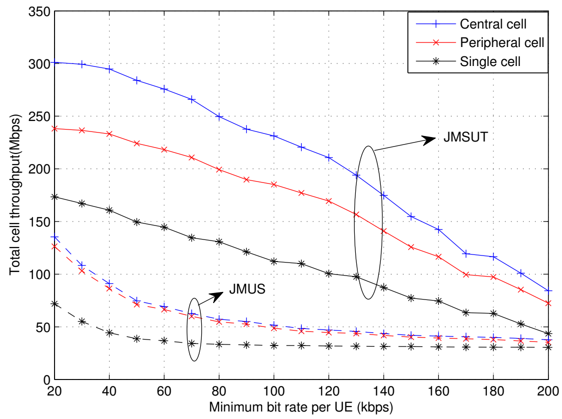


Fig. 5. Performance evaluation of JMSUT and JMUS in single and multi cell scenario using static and pedestrian users

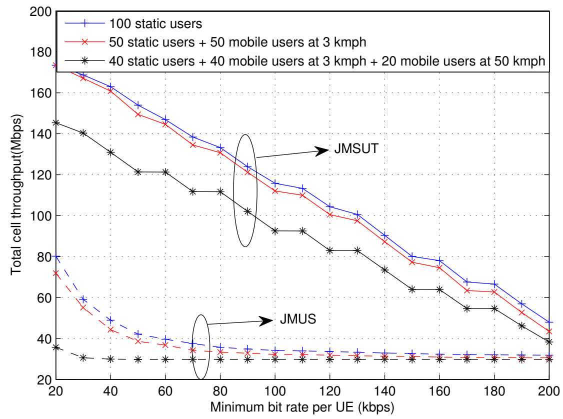


Fig. 6. Performance evaluation of JMSUT and JMUS in a scenario based on single-cell eMBMS and different combinations of static and mobile users

JMSUT instead of JMUS, since the target bit rate required in the users with worst channel conditions can be fulfilled using less amount of resources.

C. Comparison of different resource allocation strategies with different types of users

The third evaluation presents the results achieved in a single-cell multicast scenario using different combinations of users, such as static, pedestrian, and vehicular users.

The service throughput achieved using several deployments of different combinations of users is presented in Fig. 6. It can be observed that scenarios with static and pedestrian users can achieve similar service throughput, slighly better when all the users are static. Only when vehicular users are incorporated to this scenario, the results in the service throughput achieved in the cell suffer an important lowering.

In addition, it is worth notting that the use of JMSUT instead of JMUS results in an important gain in terms of service throughput, regardless the combination of users in the simulated scenario.

V. Conclusions

This work proposes the use of a joint resource allocation strategy among the unicast and multicast subframes in LTE eMBMS service. It proposes the creation of different multicast subgroups to allocate the available PRBs among them for the multicast subframes, and combine it with the transmissions in unicast subframes used to serve the users with worst channel conditions, in such a way this joint strategy maximizes the service throughput in the cell.

The performance evaluation of the proposed algorithm has shown how it can greatly improve, in terms of service throughput, the results achieved using CMS (i.e. one multicast group based on the user with the worst channel conditions), or JMUS strategy proposed in [7] (i.e. joint multicast and unicast transmissions using only one multicast group based on the joint optimization). At the same time, JMSUT algorithm allows all the users to achieve the minimum required bit rate. It is worth noting that the creation of different multicast subgroups results in users with good channel conditions can be served using high bit rates, and users with worse conditions can be served with the minimum target bit rate. Thus, the proposed algorithm allows the system to maximize the service throughput in the cell, at the time it guarantees a minimum service level for all the users.

In addition, the evaluation of JMSUT in a multi-cell multicast scenario has presented significant higher performance, in terms of service throughput, than in single-cell multicast scenario. Since the channel conditions of the UEs are enhanced using a 7-cell MBSFN area, especially those users which are placed at cell edge, leading to a higher gain in service throughput when the JMSUT strategy is used.

Finally, the evaluation of scenarios with different combinations of users has illustrated the gain achieved using JMSUT, independently of the mobility of the users. Although the service throughput is lowered with vehicular users, it happens regardless the resource allocation strategy used, and the throughput gain using JMSUT is achieved for all the combinations of users simulated.

In future work, the use of JMSUT strategy with other different cost functions, such as Proportional Fairness (PF) algorithm, will be evaluated in order to maximize the total throughput of the service increasing the fairness among all the users. Furthermore, the introduction of memory to the JMSUT algorithm will be analyzed to increase the fairness among users without lowering the total service throughput.

Acknowledgment

This work was supported in part by the Spanish Ministry of Economy and Competitiveness, National Plan for Scientific Research, Development and Technological Innovation (INNPACTO subprogram), LTExtreme project (IPT-2012-0525-430000), and the project TEC2014-59255-C3-3-R (ELISA).

References

[1] "Report - M2M Global Forecast & Analysis 2012-22," Machina Research, Tech. Rep., 2013.

[2] J. Monserrat, J. Calabuig, A. Fernandez-Aguilella, and D. Gomez-Barquero, "Joint delivery of unicast and e-mbms services in lte networks," *Broadcasting, IEEE Transactions on*, vol. 58, no. 2, pp. 157–167, 2012.

[3] *"Introduction of the multimedia broadcast/multicast service (MBMS) in the radio access networks (RAN)-Stage 2 (Release 9)"*, 3GPP TS 25.346 v9.1.0, Mar 2010.

[4] *"Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2"*, 3GPP TS 36.300 v11.7.0, Sep 2013.

[5] R. Afolabi, A. Dadlani, and K. Kim, "Multicast scheduling and resource allocation algorithms for ofdma-based systems: A survey," *Communications Surveys Tutorials, IEEE*, vol. 15, no. 1, pp. 240–254, 2013.

[6] G. Araniti, M. Condoluci, L. Militano, and A. Iera, "Adaptive Resource Allocation to Multicast Services in LTE Systems," *Broadcasting, IEEE Transactions on*, vol. 59, no. 4, pp. 658–664, Dec 2013.

[7] A. d. l. Fuente, A. Garcia Armada, and R. P. Leal, "Joint Multicast/Unicast Scheduling with Dynamic Optimization for LTE Multicast Service," in *European Wireless 2014; 20th European Wireless Conference; Proceedings of*, May 2014, pp. 1–6.

[8] G. Monghal, K. Pedersen, I. Kovacs, and P. Mogensen, "Qos oriented time and frequency domain packet schedulers for the utran long term evolution," in *Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE*, 2008, pp. 2532–2536.

[9] *"Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures"*, 3GPP TS 36.213 v11.4.0, Sep 2013.

[10] F. Capozzi, G. Piro, L. Grieco, G. Boggia, and P. Camarda, "Downlink packet scheduling in lte cellular networks: Key design issues and a survey," *Communications Surveys Tutorials, IEEE*, vol. 15, no. 2, pp. 678–700, 2013.